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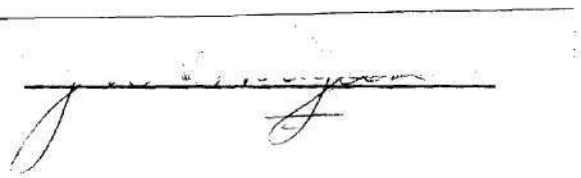

AN EXPERIMENTAL INVESTIGATION OF THE VISCOSITY OF STEAM AT HIGH PRESSURES AND TEMPERATURES

A THESIS

Presented to

The Faculty of the Graduate Division

by

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AN EXPERIMENTAL INVESTIGATION OF THE VISCOSITY

OF STEAM AT HIGH PRESSURES AND TEMPERATURES

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Finally, the author thanks his wife, Peggie, for her patience and sacrifice during this first year of graduate study.

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SUMMARY

Values for the viscosity of supercritical steam obtained by Barnett (7) from the annular viscometer are about 10 per cent lower than the values obtained with capillary viscometers by other investigators. The purpose of this research was to obtain new viscosity data from Barnett's apparatus in anticipation that a second, independent investigation of the viscosity of steam would reveal the causes for Barnett's lower values. Consequently, Barnett's apparatus was completely rebuilt with care being taken to eliminate experimental error.

Over 170 viscosity data points were obtained between 390°C and 550°C at pressures of 3750 psia, 5000 psia, 7500 psia, and 10,000 psia. The data tend to agree with Whitelaw's (8) results at 3750 and 5000 psia, and with Barnett's results at 7500 and 10,000 psia. No conclusions, therefore, could be drawn concerning the validity of the various sets of data, and the discrepancy between the capillary viscometer data and the annular viscometer data still exists (at least at 7500 and 10,000 psia). The annular viscometer is well suited for determining the viscosity of dry gases at elevated temperatures and pressures and it is recommended for such studies. It is also recommended that further studies be initiated utilizing

viscometers other than the capillary or annular types in expectation that perhaps a third method of determining viscosity will clear up the discrepancies noted.

CHAPTER I

INTRODUCTION

Definition of the Problem

As metallurgical progress is made steam power plants are able to operate at higher temperatures and pressures in order to realize increased thermal efficiencies. In order to proceed with the design of components for power plants, the properties of the working fluid, steam, must be known. Since viscosity data are necessary for the evaluation of several important heat transfer and fluid flow parameters (for example, Reynold's number, Prandtl number, and Grashof number), it is essential that the viscosity of steam be known at the pressures and temperatures anticipated in future power plant cycles.

History

The viscosity of supercritical steam has been measured by several investigators including Hawkins, Solberg and Potter (1), Sigwart (2), Timrot (3), Timrot and Khlopkina (4), Schmidt and Mayinger (5), Thomas and Jackson (6), Barnett (7), Whitelaw (8), and most recently by Ray (9).

Timrot (3), Timrot and Khlopkina (4), Schmidt and Mayinger (5), Whitelaw (8), and Ray (9) all used capillary-type viscometers. Thomas and Jackson (6) and Barnett (7)

obtained their results using annular-type viscometers. Although both types of viscometers are similar in principle the procedures and the apparatus used in obtaining data differ considerably. Barnett's results are about 10 per cent lower than the mean of the other investigators' results.

Purpose of the Research

Barnett's data were the only substantial data obtained with an annular type viscometer in the high pressure (3750-10,000 psi) regime prior to this investigation. Because Barnett's results are lower than those of other investigators it was felt that perhaps some systematic error may have been responsible for the discrepancies. It was further felt that a complete rebuilding, recalibration, and reuse of Barnett's apparatus might reveal the cause for the discrepancies noted. Therefore, the main purpose of this investigation was to make a second, independent determination of the viscosity of steam using Barnett's system after it had been rebuilt to minimize experimental error in expectation that the cause for his lower viscosity values would be discovered.

CHAPTER II

EQUIPMENT AND INSTRUMENTATION

Governing Equation

For the case of an incompressible Newtonian fluid passing through a horizontal annulus under the conditions of steady, fully-developed, laminar flow, the kinematic viscosity of the fluid may be determined from the following equation:

$$\nu = CC_t \frac{\Delta p}{W} \tag{1}$$

where

ν = kinematic viscosity

Δp = pressure drop across annulus length

W = weight flow rate of fluid

C = constant containing annulus dimensions

C_t = temperature correction factor for C.

For a detailed derivation of the above equation the reader is referred to references (7), (10), and (11).

To evaluate the constant, C, from the annulus dimensions would require that the dimensions be known to an extreme degree of accuracy. It was, therefore, necessary that the annulus be calibrated with some fluid whose viscosity was already known. The temperature correction

factor, C_t, was necessary to account for thermal expansions of the annulus components and was evaluated by calibrating the annulus at elevated temperatures. The correction factor was arbitrarily assigned a value of unity at room temperature ($80^{\circ}F$).

No pressure correction was necessary as the annulus was pressure-compensated.

Equipment

General

The equipment used in this investigation is shown in Figures 1 and 2. Triple-distilled water was deaerated by boiling it vigorously in pyrex bottles, and then stored in five-gallon collapsible plastic bottles. From the bottles the water passed through a heat exchanger, through an automotive gasoline filter, and into the high pressure pump. The pump was of a reciprocating, variable stroke design capable of producing a pressure of 30,000 psi. After passing through the pump the water was introduced into a room temperature surge chamber and then into a heated surge chamber. The surge chambers were designed to reduce pressure pulsations from the pump. The system pressure tap was located after the heated surge chamber. Then came a 16 foot long preheater coil located in a small metallurgical furnace. The preheater furnace temperature was regulated by a continuous-type combination recorder and controller. The preheater coil was connected directly

to the annulus autoclave which was located in another furnace. In order to prevent heat losses between the preheater and the annulus the furnaces were butted up against each other. From the preheater coil the steam flowed through the annulus, into a condenser, into a filter, through a throttling valve and capillary tube, and finally into the flow exit tube from which the condensate was collected in a small bottle. All tubing used on the high pressure part of the apparatus was stainless steel (type 304).

Annulus

The annulus used in this investigation is shown schematically in Figure 3 and was the annulus Barnett (7) refers to as Annulus No. 2. It was located inside a high pressure autoclave which was sheathed in 1/4 inch thick copper to help in obtaining a uniform temperature distribution.

The outer tube of the annulus was made from standard 9/16 inch o.d. type 304 stainless steel tubing. It was ballized with a 0.3125 inch diameter tungsten-carbide ball and polished with jewler's rouge. The inner tube was made from standard 3/8 inch o.d. type 304 stainless steel tubing which was machined to size and also polished with jeweler 's rouge. Figure 3 shows the relatively long calming section before the upstream pressure tap. The calming section was necessary to ensure fully-developed flow in the annulus test section between the pressure taps.

Instrumentation and Controls

Pressure Drop Measurement

The problem of measuring small pressure differences at high static pressures was one of the restrictions that prevented Thomas (6) from taking viscosity data at pressures greater than 5,000 psi. Barnett (7) reported on an optical absorption cell system which was later refined by Whitesides (10) and used in the present study with minor improvements. The manometer is shown in Figures 1, 2, and 4 and consisted in part of a commercially available optical absorption cell fitted with a 20-power microscope containing a hair-line lens. The absorption cell had a quartz window which allowed the fluid in the cell to be observed through the microscope. The upper fitting on the absorption cell was connected to the downstream pressure tap on the annulus, while the lower fitting was connected through a U-tube of flexible stainless steel tubing to a reservoir. The reservoir was, in turn, connected to the upstream pressure tap on the annulus (see Figure 1). After assembly the manometer was filled with mercury until a mercury meniscus appeared in the quartz window.

The optical cell was swivel-mounted on a finely threaded shaft which ran through a threaded collar secured to the table. Thus, the optical cell could be raised and lowered by turning the threaded shaft. By knowing the thread pitch and the number of turns made by the shaft in

moving the cell, it was possible to determine accurately the change in height of the cell. The manometer, therefore, had one stationary leg and one movable leg which allowed it to be used as a null-type manometer with the hairline as the reference point. Although the threaded shaft was fitted with a micrometer type wheel having divisions on its periphery representing 0.0001 inches of vertical movement of the cell, an observer could not detect a change of the meniscus less than 0.001 inches.

The successful operation of the manometer depended upon having both legs free of air bubbles. For this reason, the system was evacuated with a vacuum pump before water was introduced into the system, and bleed valves were located in the manometer lines so that any entrapped air could be periodically released.

Temperature Measurement

The annulus temperature was measured with an iron-constantan thermocouple shielded in stainless steel and calibrated by the supplier, the Thermo-Electric Company. The emf was measured by a Leeds and Northrup model 8686 portable potentiometer. The preheater temperature was not measured directly, but was used as the input signal to the preheater furnace controller. The annulus temperature was used as the reference signal for the controller. Using this arrangement the controller maintained the preheater temperature within $5^{o}F$ of the annulus temperature. The annulus temperature is believed to be accurate to within 1^{o}Centigrade.

System Pressure Measurement

The system pressure was measured by a dead-weight tester manufactured by the American Instrument Company and guaranteed by them to be accurate within ±20 psi. The tester was fitted with a microswitch which turned the pump off whenever the system pressure rose, and turned it back on when the pressure fell. The pressure fluctuation from the time the pump cut off until it restarted was less than 50 psi.

Since the smallest weight used for the dead weight tester represented 10 psi. and since the piston was kept floating at all times during a run, it is believed that the pressure was measured correctly to within ±20 psi.

Mass Flow Measurement

The steam mass flow rate through the annulus was determined by weighing the condensate collected in a long necked bottle during a given period of time. An analytical balance was used to determine the mass of the bottle and its contents while the time interval was measured with an electric timer. The masses of the empty bottles were checked periodically.

The mass of condensate was determined to within 0.02 grams and the time interval was measured to within one second.

Furnace Controls

The annulus furnace temperature was controlled by a Brown on-off type controller. Although the furnace temper-

ature fluctuated several degrees due to the mode of operation of the controller, the fluctuations were damped out by the large thermal inertia of the copper sheathed stainless steel autoclave containing the annulus. No fluctuations in the annulus temperature were detected during tests.

The preheater furnace temperature was controlled by a Brown combination recorder and continuous-type controller. The continuous control was necessary due to the small thermal inertia of the preheater coil. A powerstat was used to regulate the temperature of the heated surge tank.

CHAPTER III

EXPERIMENTAL PROCEDURE

Calibration of Annulus

As previously mentioned, the constant C had to be determined by calibrating the annulus with a fluid whose viscosity is known. The fluids used to calibrate the annulus were argon and nitrogen. Values for the viscosity of these gases were obtained from data published by the United States Bureau of Standards (12).

During a calibration run, nitrogen or argon (which was used only to verify the first calibration run made with nitrogen) was passed through the annulus and fed into a wet test meter which measured the volume rate of flow. The pressure drop across the annulus was measured by a null-type micromanometer using water as the manometer fluid. An electric timer was used to measure the time required to pass a given amount of nitrogen (usually 0.3 ft^3) through the system. The annulus constant was checked before and after each isobar was run and also after any extensive modifications were made to the system. After the 10,000 psi isobar data were taken the annulus was inadvertently allowed to overheat (go above 1300^{o}F.) and it was impossible to recheck the annulus constant. However, prior to the overheating the constant, C, was found

to be a constant for the Reynolds number range 20 to 130. All of the experimental data were taken within this range of Reynolds numbers. In all cases (except for the isobar noted above) the values found for C before and after runs were made were within 1.4 per cent of the value used for C. The constant is plotted versus Reynolds number in Figure 8.

The temperature correction factor, C_t, was determined before any viscosity data were taken and was not checked again. C_t is plotted versus temperature in Figure 9.

Steam Viscosity Measurements

The water used to generate the steam was triple-distilled and thoroughly deaerated before use. After the flow was started, the system was allowed to reach steady-state conditions before any readings were attempted. Using the methods of control previously discussed, the annulus temperature was held within $1^{\circ}F$ during any test run and within $2^{\circ}F$ during a series of runs. The preheater temperature was always within $5^{\circ}F$ of the annulus temperature. The annulus temperature was monitored by a temperature recorder and this recorder indicated when steady state conditions were reached. The preheater, having less thermal inertia, would come up to temperature well before the annulus temperature stabilized itself.

Before an experimental run was attempted the pump stroke was adjusted so that the pump would run continually

while the data were being taken. After steady flow conditions had been established, one leg of the manometer was valved off from its side of the annulus and exposed to the same pressure as the other leg. This allowed the manometer zero reading to be taken without stopping the flow in the annulus. After the zero reading was recorded, the manometer was restored to its normal operation in order that the pressure drop across the annulus could be read. After the pressure drop, annulus temperature, and preheater temperature were recorded, a bottle was placed under the flow exit tube. An electric timer was started at the precise moment that the bottle was placed to catch the condensate flow. In order to reduce evaporation effects, the bottle neck extended well over the flow exit tube.

After 200 seconds had elapsed, the bottle was removed and capped immediately, the annulus and preheater temperatures recorded again, and the final manometer reading taken. (It should be noted that the difference between the initial and final manometer readings was always less than 0.002 inches.) The manometer zero was then rechecked and was invariably within 0.002 inches of the initial zero reading. Averages of the initial and final readings were used for computation purposes. A series of five runs were usually attempted at a particular pressure and temperature. After the final run in a series, the bottles were weighed on an analytical balance to determine the amount of condensate collected.

Thus, by knowing the annulus constant, CC_t; the pressure drop, Δp; and the weight flow rate of steam, W; equation 1 could be used to determine the kinematic viscosity. The experimental data were fed into a Burroughs 220 digital computer which calculated the viscosity values.

CHAPTER IV

RESULTS

The experimental data are plotted as kinematic viscosity in Figure 5. Whitelaw's (8) results and Barnett's (7) data are also shown for purposes of comparison. It should be noted that Whitelaw's recommended curves had to be interpolated in order to obtain his values for the isobars shown (except the 704 kg/cm^2 isobar which was compared to Whitelaw's 700 kg/cm^2 results directly). The method of interpolation involved cross-plotting Whitelaw's curves to yield a family of isothermal lines as shown in Figure 6. Whitelaw's data at 250 kg/cm^2 consisted only of data at two temperatures (380°C and 433°C) from which he extrapolated his recommended curve to over 600°C. It is felt, therefore, that the interpolation of Whitelaw's curves to yield results at 264 kg/cm^2 (3750 psia) may be subject to considerable error due to the scarcity of experimental data at 250 kg/cm^2.

Very close agreement with Whitelaw's values is indicated at both 3750 and 5000 psia at temperatures above 430°C; although at 7500 and 10,000 psia the present study and Barnett's data are in close agreement.

The kinematic viscosity was converted to absolute viscosity using density values from reference (13). Figure

7 shows the absolute viscosity values obtained. Also shown on this figure is the viscosity equation recommended by reference (14) with the constants modified to fit the data. Excellent agreement with the data is obtained by use of this equation which is:

$$\mu = 1.805 \times 10^{-8} \times T^{1.5} \exp\left[\frac{1300\rho}{T} - \frac{T}{1865}\right] \quad (2)$$

where

μ = viscosity, gm/cm-sec

T = absolute temperature, ^{o}K

ρ = density, gm/cm^3

Equation (2), however, does not fit the atmospheric data of Latto (15) very well. At atmospheric pressure the term containing the density becomes insignificant, leading to the equation:

$$\mu_{atmos} = 1.805 \times 10^{-8} \times T^{1.5} \exp\left[-\frac{T}{1865}\right] \quad (3)$$

which may be compared to the equation which fits Latto's data (from reference (14)):

$$\mu_{atmos} = 2.05 \times 10^{-8} \times T^{1.5} \exp\left[-\frac{T}{1865}\right] \quad (4)$$

Thus equation (2) underestimates the atmospheric dynamic viscosity by about 12 per cent. It is, of course, possible that the addition of other terms into equation (2) could result in a better fit, but the findings of reference (14)

indicate that the present form of the equation represents the majority of the experimental data satisfactorily.

Error Analysis

A summary of the magnitude of the errors involved in the present experimental investigation is as follows:

Temperature Measurement

As previously stated, the annulus temperature is considered to have been measured accurately to within 1^{o} Centigrade.

Pressure Measurement

The system pressure is felt to be correct to within 20 psi as previously discussed.

Mass Flow Rate

Since the amount of condensate collected was always greater than 10 grams, the mass determination should be correct to within 0.2 per cent. The time interval used for a run was 200 seconds with a possible error of 1 second, which leads to a percent accuracy in measuring the time of 0.5 percent. Therefore, the mass flow rate is believed to be accurate within 0.7 per cent.

Pressure Drop

The height of the mercury-water column in the manometer was always at least 0.100 inches. Since the error in determining the height was within 0.002 inches, the pressure drop is believed to be accurate within 2 percent.

Annulus Constant

The annulus constant was checked before and after each isobar was investigated (except for the 10,000 psia isobar) and was in each case within 1.4 per cent of the value used. Therefore, the annulus constant is believed accurate to within 1.4 per cent.

Overall Accuracy

Using equation (1) and the above error assessments the overall accuracy should be within 4 per cent.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

From the data taken no conclusions could be reached concerning the existence of systematic errors in Barnett's investigation. Although the results of the present investigation agree well with Whitelaw's results at 3750 psia and 5000 psia, there is equally good agreement with Barnett's results at 7500 psia and 10,000 psia; making general conclusions as to the validity of one set of data over the other impossible.

There still exists, then, the discrepancy between the viscosity values obtained with capillary-type viscometers and the results obtained by use of the annular-type viscometer. It should be noted, however, that the differences are of such a magnitude that satisfactory results will be obtained in engineering calculations regardless of which values are used.

The annular viscometer is well suited for the determination of the viscosity of dry gases at elevated temperatures and pressures as discovered by the excellent data obtained in the calibration procedure using nitrogen. The question as to which results are correct may be resolved by other investigations using viscometers other than the capillary or annulus types. It is, therefore, recommended that

such studies be initiated whenever feasible.

APPENDIX A

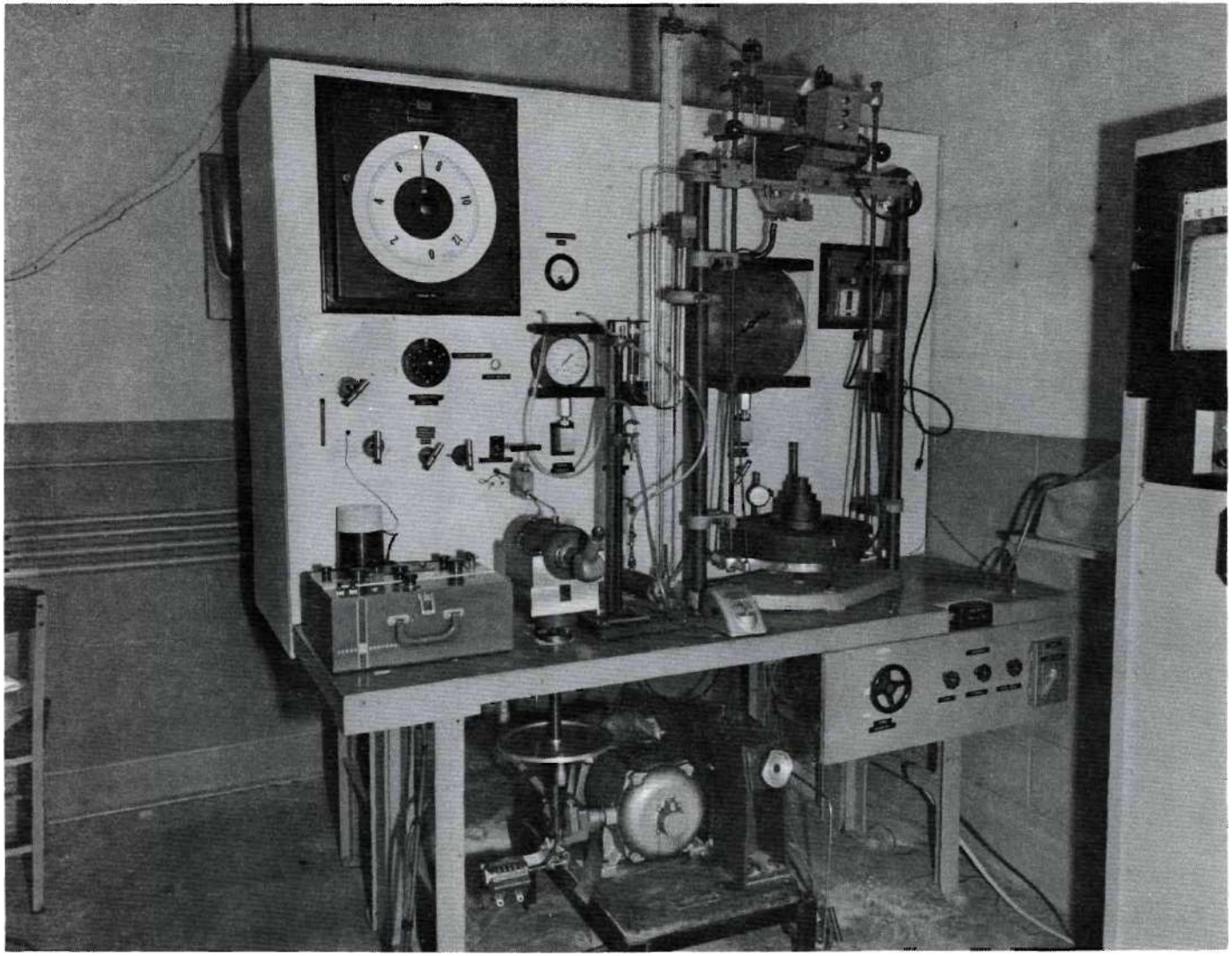

Figure 1. Photograph of Experimental Apparatus.

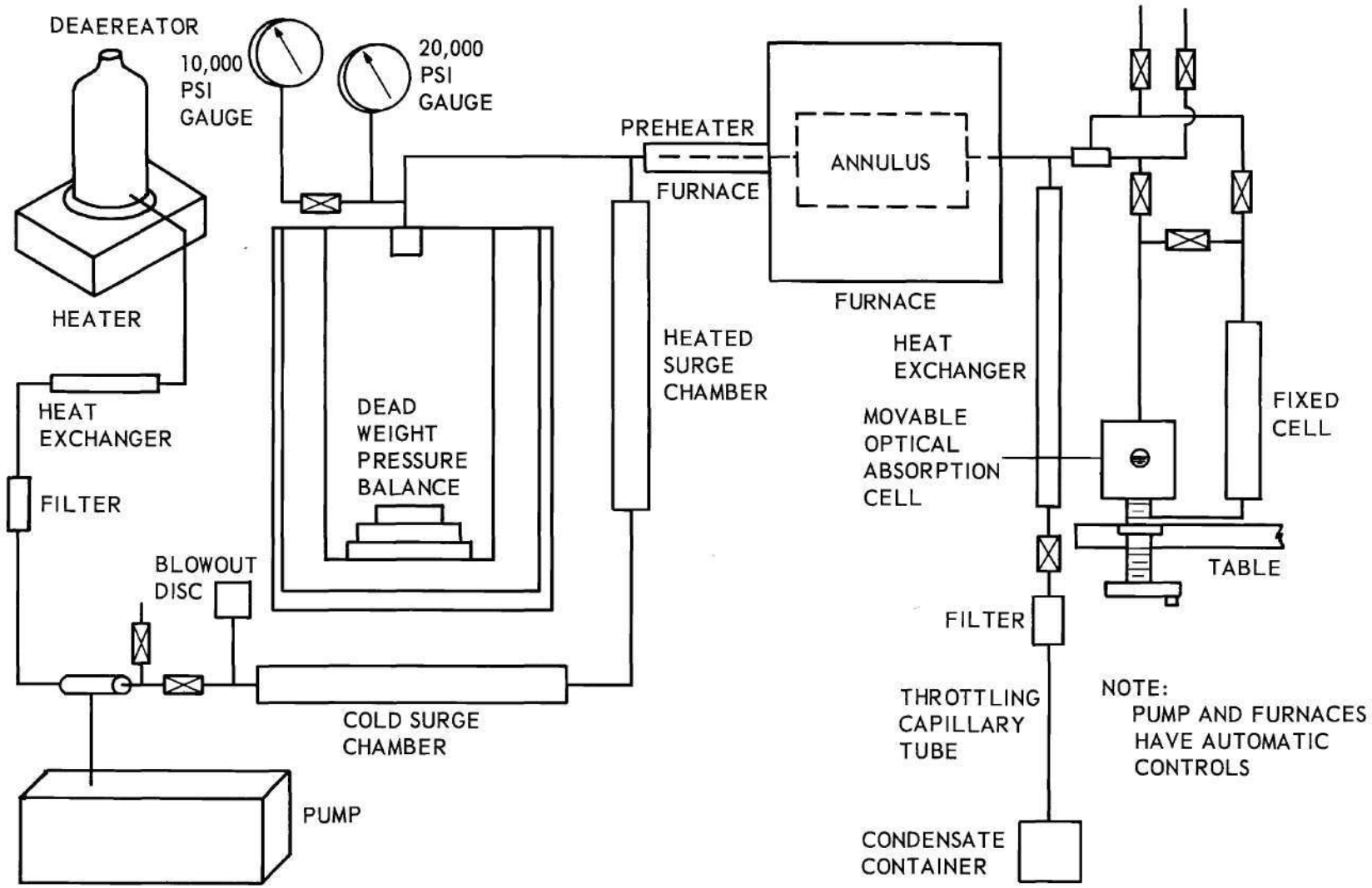

Figure 2. Schematic Diagram of Experimental Apparatus.

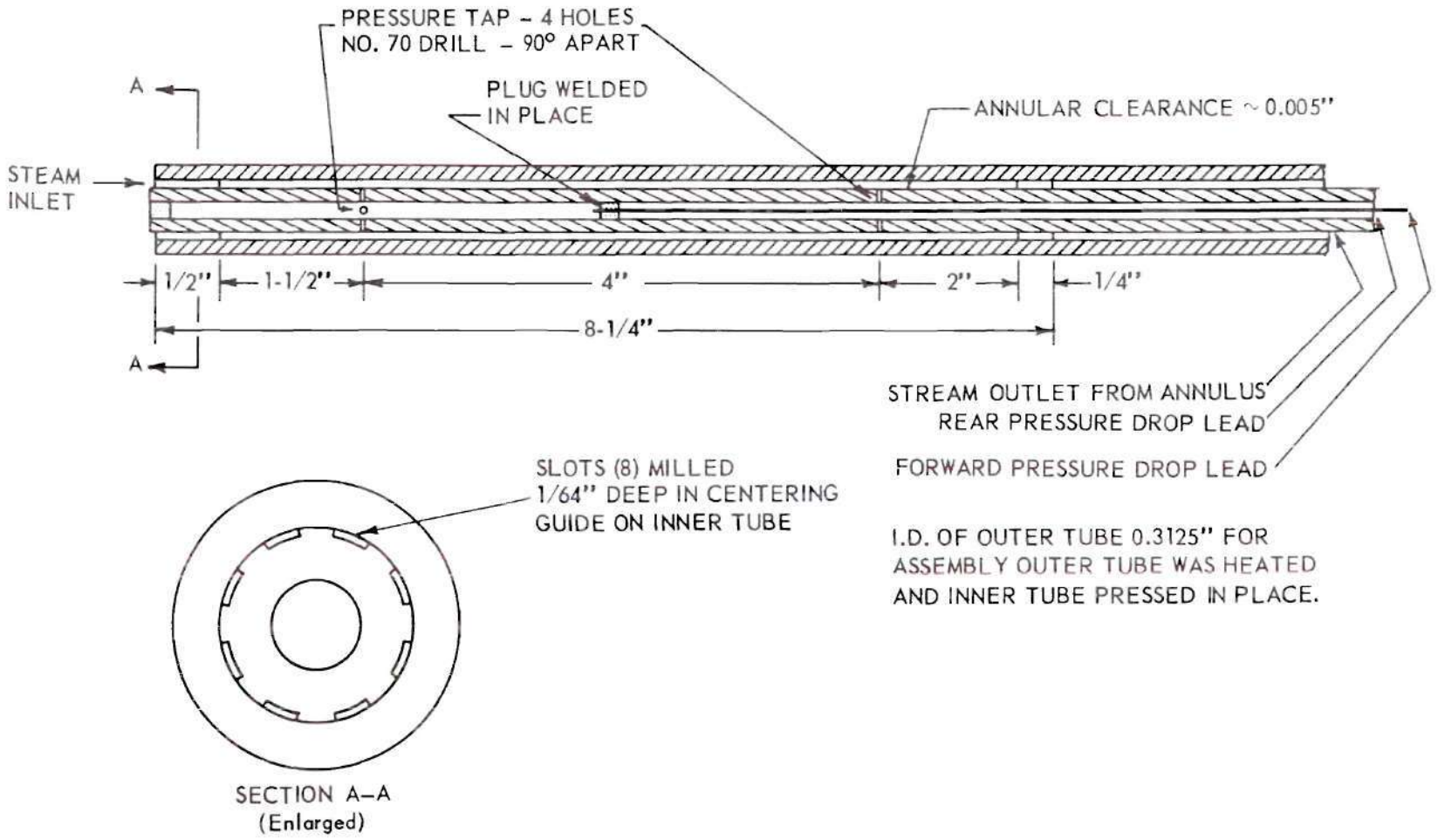

Figure 3. Schematic Drawing of Annulus Assembly.

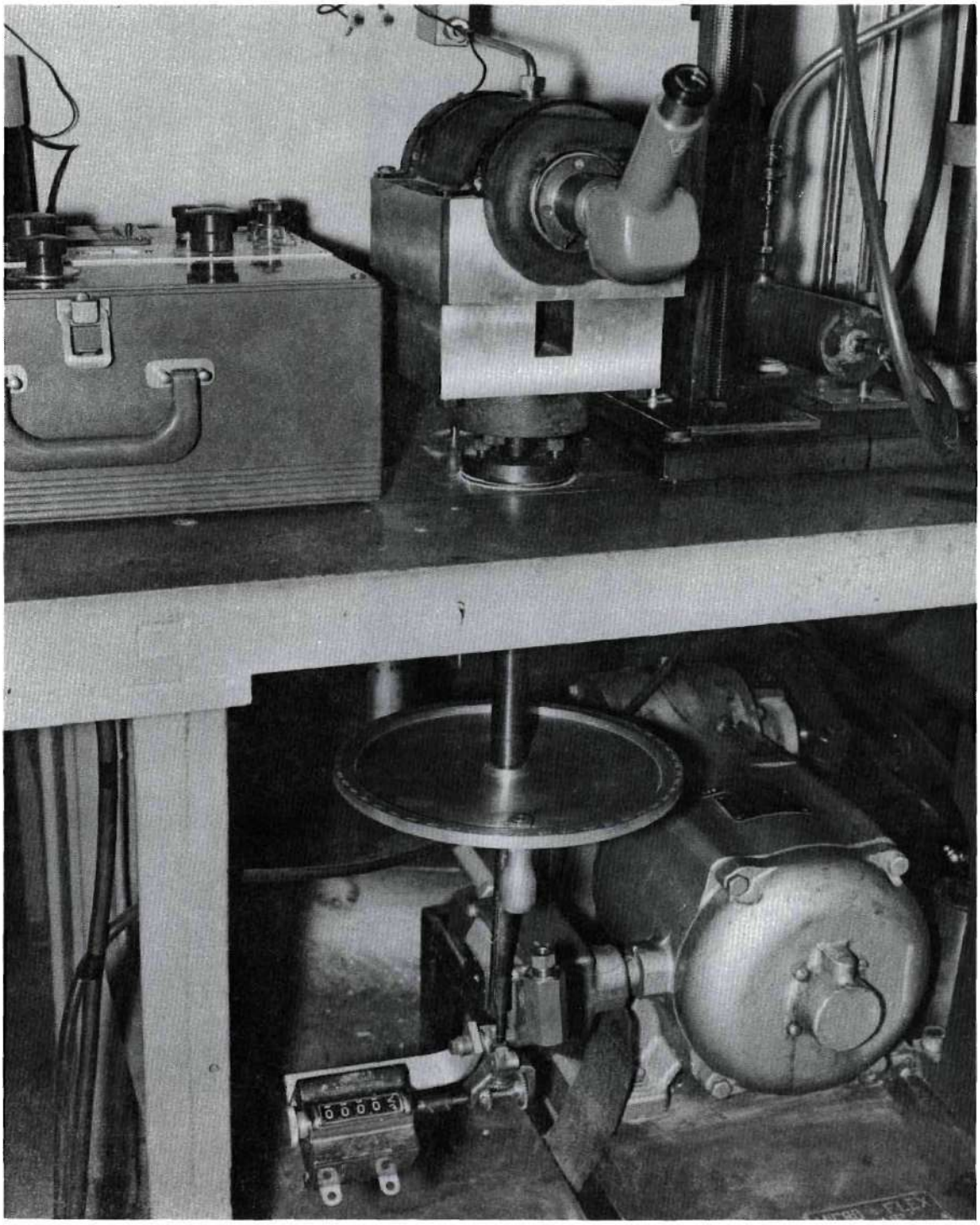

Figure 4. Photograph of Absorption Cell and Microscope.

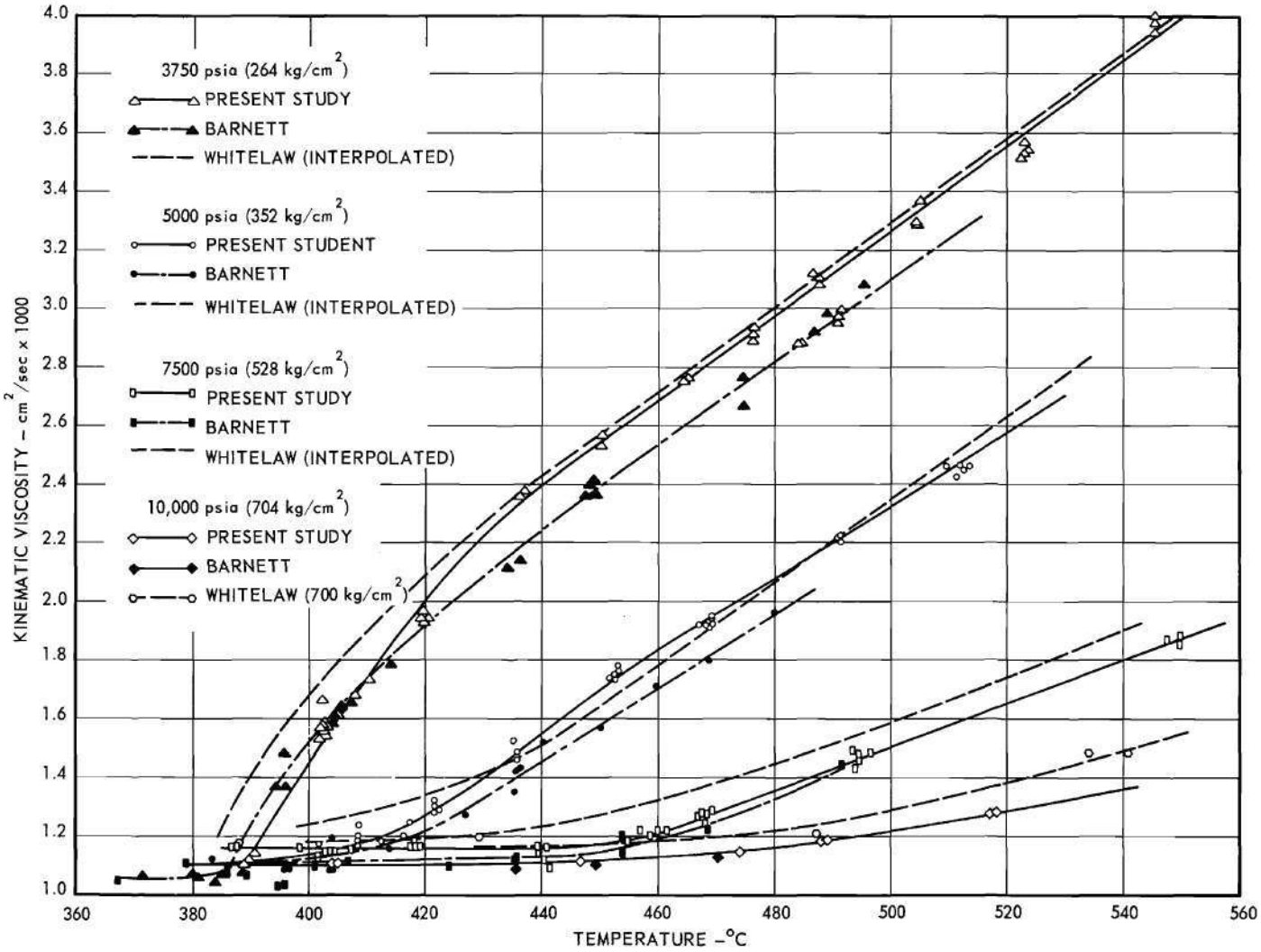

Figure 5. Kinematic Viscosity of High Pressure Steam.

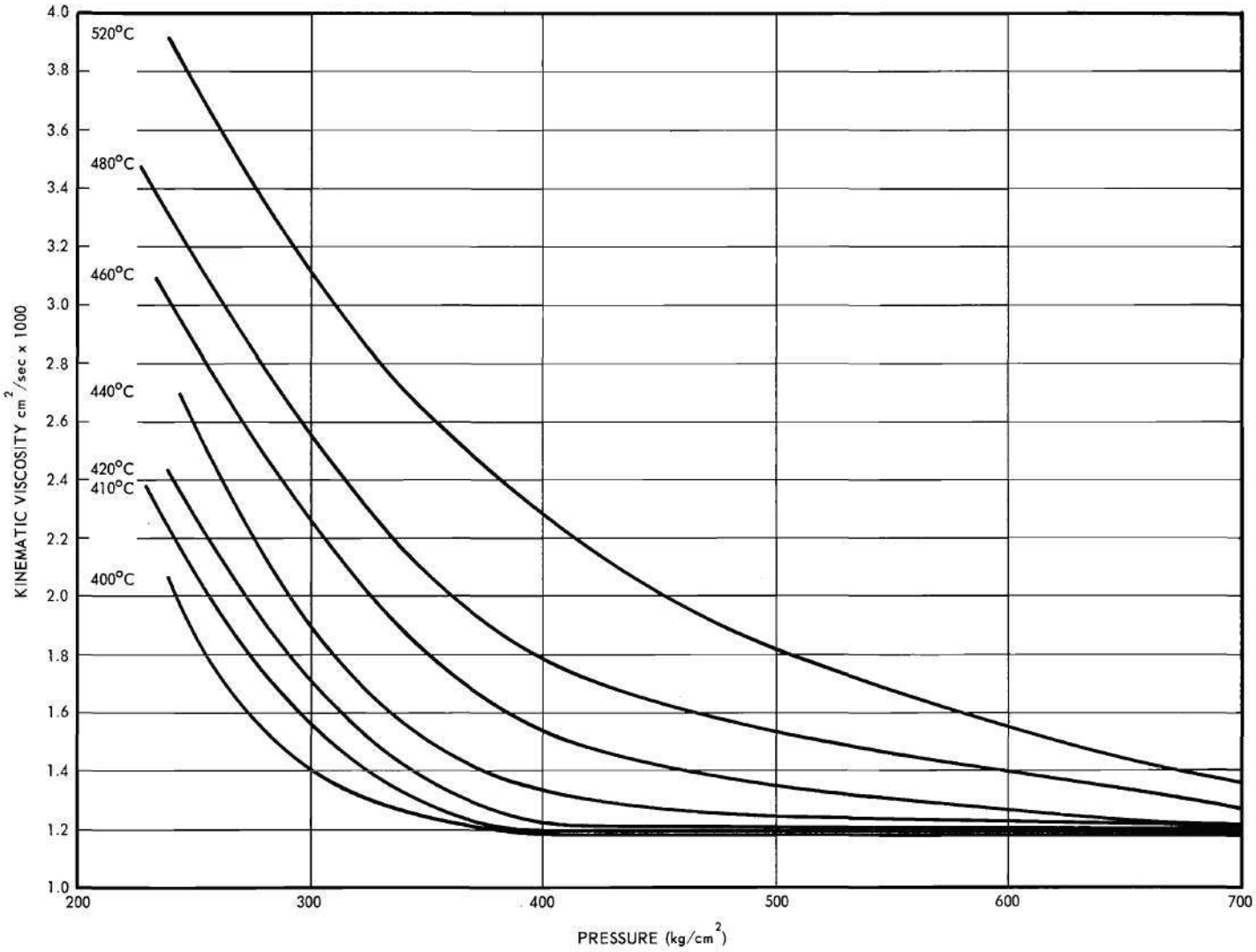

Figure 6. Cross-plot of Whitelaw's Recommended Curves.

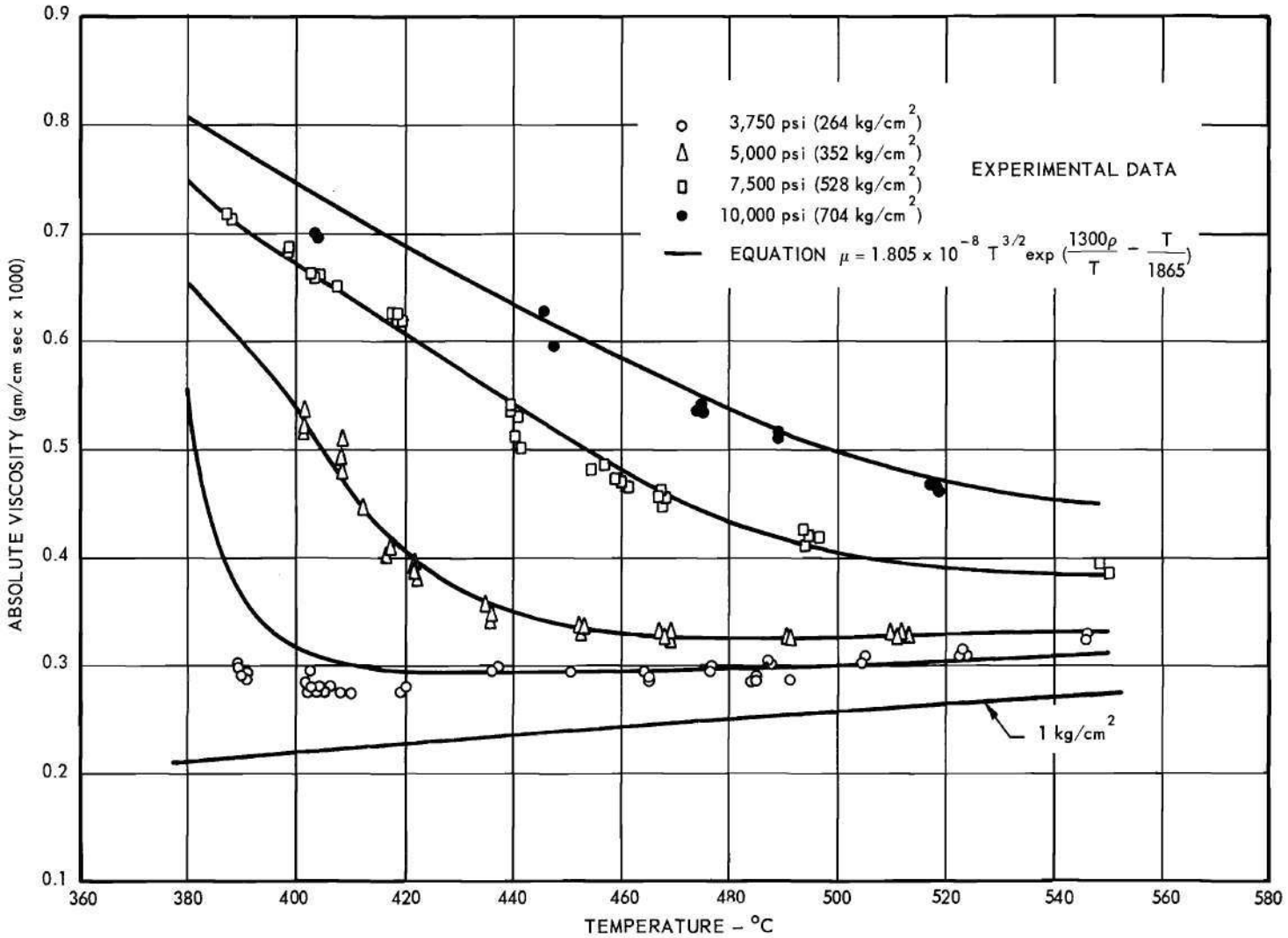

Figure 7. The Absolute Viscosity of High Pressure Steam.

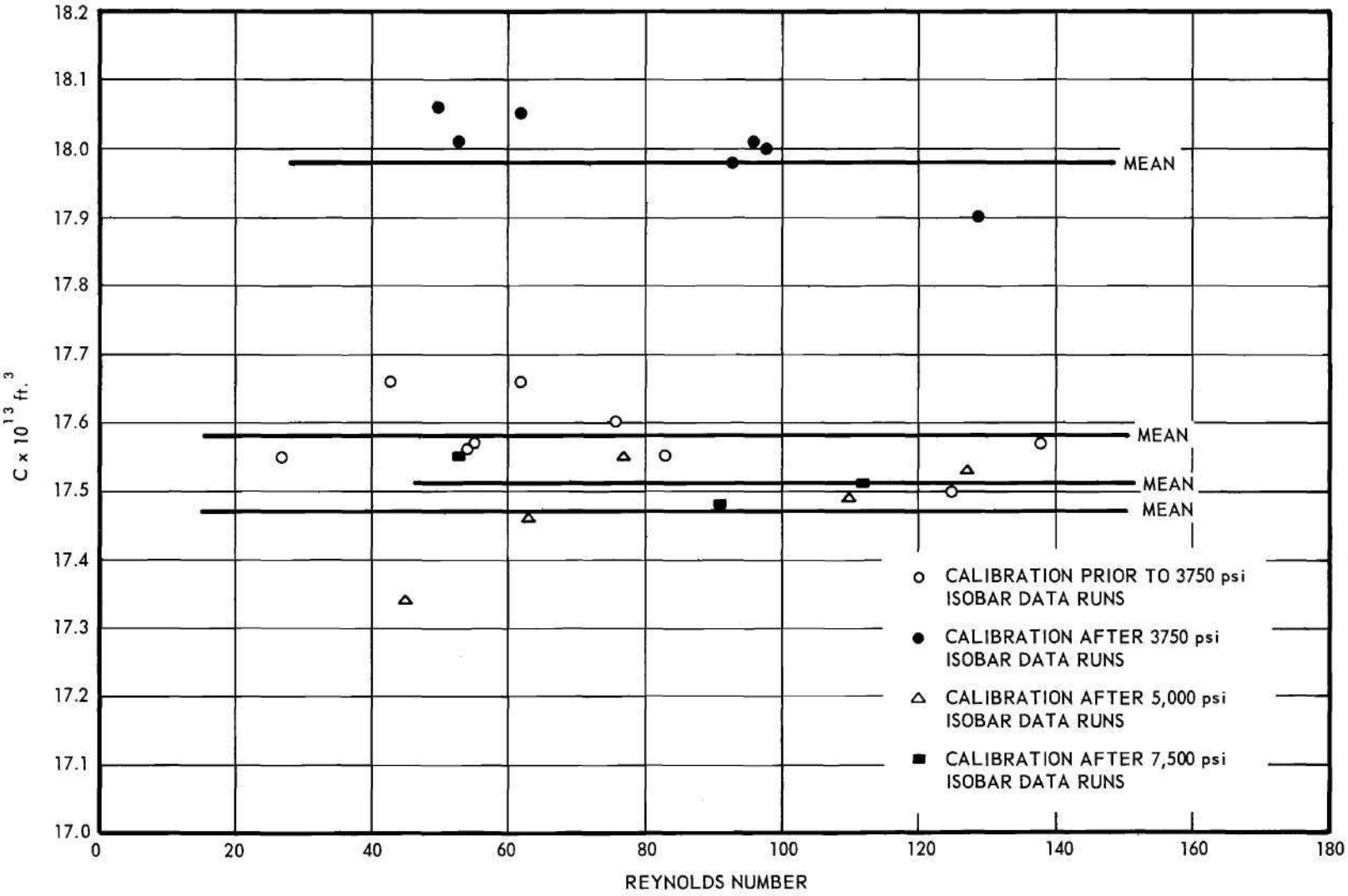

Figure 8. Annulus Constant vs. Reynolds Number.

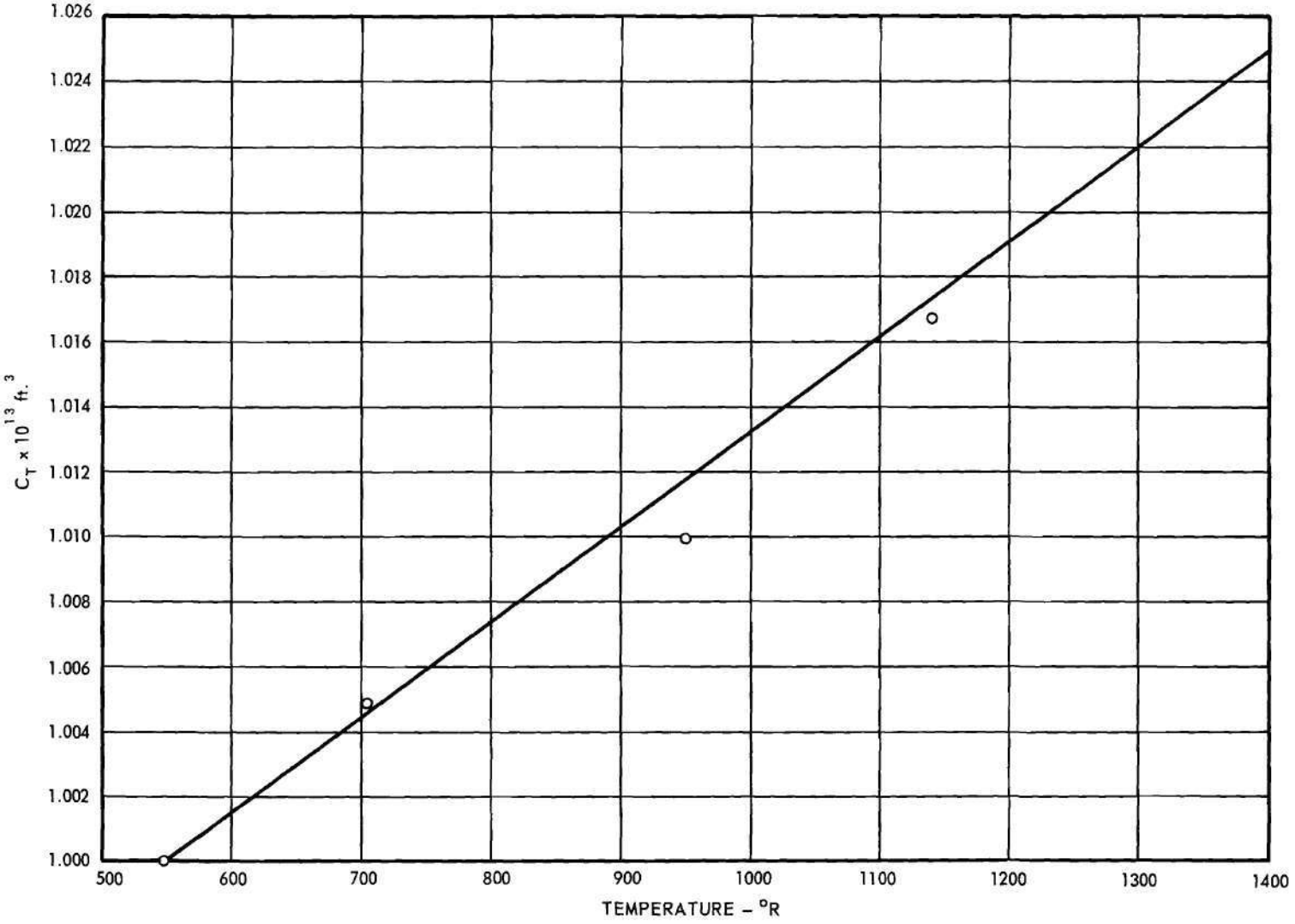

Figure 9. Annulus Temperature Correction Factor vs. Temperature.

APPENDIX B

Table 1. Viscosity of Steam - Experimental Data

P (psia)	T (Deg. Cent)	Reynolds No.	ν (cm^2/sec) x 1000	Density (gm/cc)	μ (gm/cm sec) x 1000
3750	389.2	76.5	1.107	.269	.297
3750	389.7	73.4	1.123	.269	.302
3750	390.3	74.0	1.136	.254	.288
3750	390.3	71.6	1.141	.254	.290
3750	390.9	70.3	1.143	.254	.290
3750	402.0	60.3	1.581	.180	.284
3750	402.0	61.6	1.572	.180	.283
3750	402.0	97.9	1.537	.180	.276
3750	402.0	57.2	1.581	.180	.284
3750	402.5	50.8	1.665	.178	.296
3750	402.5	56.6	1.563	.178	.278
3750	402.5	59.9	1.591	.178	.283
3750	402.5	59.4	1.589	.178	.282
3750	403.1	58.9	1.599	.176	.281
3750	403.1	55.8	1.586	.176	.279
3750	404.2	54.8	1.584	.173	.274
3750	404.2	52.9	1.611	.173	.278
3750	404.2	87.0	1.613	.173	.279
3750	404.7	53.4	1.597	.172	.274
3750	404.7	52.3	1.622	.172	.278
3750	405.8	81.2	1.651	.169	.279
3750	408.1	75.5	1.692	.162	.274
3750	410.3	67.4	1.739	.158	.274
3750	419.2	55.3	1.941	.143	.277
3750	419.2	54.5	1.944	.143	.278
3750	419.2	53.7	1.950	.143	.278
3750	419.2	52.9	1.956	.143	.279
3750	419.7	51.8	1.966	.143	.281
3750	436.4	58.9	2.363	.125	.295
3750	436.9	60.5	2.383	.125	.297
3750	436.9	62.2	2.375	.125	.296
3750	436.9	61.5	2.376	.125	.297
3750	450.3	42.6	2.550	.115	.293
3750	450.3	42.1	2.541	.115	.292
3750	450.3	41.7	2.539	.115	.292
3750	450.3	40.9	2.555	.115	.293
3750	450.3	40.0	2.574	.115	.296
3750	464.1	33.9	2.763	.107	.295
3750	464.7	40.0	2.705	.107	.289
3750	464.7	39.6	2.669	.107	.285
3750	476.3	54.9	2.904	.102	.296
3750	476.3	53.8	2.924	.102	.298

Table 1 (Continued). Viscosity of Steam - Experimental Data

P (psia)	T (Deg. Cent)	Reynolds No.	ν (cm^2/sec) x 1000	Density (gm/cc)	μ (gm/cm sec) x 1000
3750	476.3	53.0	2.941	.102	.299
3750	476.3	53.6	2.922	.102	.298
3750	476.3	52.9	2.929	.102	.298
3750	484.1	95.1	2.882	.099	.285
3750	484.7	90.9	2.908	.099	.287
3750	484.7	85.9	2.951	.099	.292
3750	484.7	86.4	2.915	.099	.288
3750	484.7	85.8	2.892	.099	.286
3750	486.9	44.5	3.123	.098	.306
3750	487.4	46.3	3.085	.098	.302
3750	487.4	45.6	3.111	.098	.304
3750	487.4	45.7	3.105	.098	.304
3750	487.4	45.4	3.110	.098	.304
3750	490.8	72.2	2.963	.097	.287
3750	490.8	71.7	2.965	.097	.287
3750	490.8	71.1	2.996	.097	.290
3750	490.8	70.5	2.996	.097	.290
3750	491.3	70.9	3.004	.097	.291
3750	504.6	57.6	3.296	.092	.303
3750	504.6	57.1	3.291	.092	.302
3750	504.6	56.2	3.301	.092	.303
3750	504.6	55.7	3.302	.092	.303
3750	505.2	55.7	3.379	.092	.310
3750	522.4	43.8	3.527	.088	.310
3750	523.0	44.2	3.540	.088	.311
3750	523.0	42.9	3.574	.088	.314
3750	523.5	43.8	3.554	.088	.312
3750	523.5	43.3	3.549	.088	.312
3750	545.7	55.2	3.949	.083	.327
3750	545.7	54.8	3.945	.083	.327
3750	545.7	53.5	3.985	.083	.330
3750	545.7	53.0	3.981	.083	.330
3750	545.7	51.8	4.007	.083	.332
5000	401.4	72.8	1.140	.456	.520
5000	401.4	73.3	1.136	.456	.518
5000	401.4	70.7	1.178	.456	.537
5000	401.4	73.6	1.133	.456	.517
5000	408.6	76.3	1.201	.410	.492
5000	408.6	76.8	1.190	.410	.488
5000	408.6	78.4	1.168	.410	.479
5000	408.6	73.3	1.243	.410	.509
5000	412.5	31.8	1.181	.378	.446
5000	422.5	98.6	1.291	.295	.381
5000	421.9	96.6	1.303	.298	.388
5000	421.9	96.0	1.312	.298	.391
5000	421.9	96.0	1.312	.298	.391
5000	421.9	95.2	1.324	.298	.394
5000	421.9	98.0	1.285	.298	.383

Table 1 (Continued). Viscosity of Steam - Experimental Data

P (psia)	T (Deg. Cent)	Reynolds No.	ν (cm^2/sec) x 1000	Density (gm/cc)	μ (gm/cm sec) x 1000
5000	435.8	109.1	1.491	.233	.347
5000	435.8	111.3	1.460	.233	.340
5000	435.8	109.8	1.485	.233	.346
5000	435.3	106.6	1.530	.233	.356
5000	453.0	115.0	1.764	.190	.335
5000	453.0	117.2	1.732	.190	.329
5000	452.5	115.9	1.735	.192	.333
5000	452.5	114.6	1.753	.192	.336
5000	451.9	115.8	1.740	.192	.334
5000	469.1	120.4	1.925	.168	.323
5000	469.1	118.8	1.958	.168	.329
5000	469.1	119.4	1.945	.168	.326
5000	469.1	119.9	1.944	.168	.326
5000	469.1	119.8	1.943	.168	.326
5000	491.3	122.6	2.204	.147	.323
5000	491.3	121.1	2.227	.147	.327
5000	490.8	121.2	2.230	.147	.327
5000	490.8	121.2	2.229	.147	.327
5000	490.8	122.1	2.216	.147	.325
5000	417.5	110.6	1.248	.326	.407
5000	416.4	112.1	1.201	.333	.400
5000	468.0	122.1	1.923	.169	.325
5000	469.1	121.7	1.947	.168	.327
5000	468.6	121.3	1.917	.171	.327
5000	466.9	120.8	1.926	.171	.329
5000	511.9	119.1	2.472	.134	.331
5000	511.3	121.5	2.436	.134	.326
5000	509.6	119.9	2.465	.134	.330
5000	512.4	120.5	2.455	.134	.329
5000	513.5	120.9	2.464	.133	.327
7500	387.0	76.8	1.167	.615	.718
7500	387.5	76.5	1.171	.613	.718
7500	388.1	77.0	1.169	.610	.713
7500	398.6	80.1	1.171	.584	.684
7500	398.6	80.4	1.169	.584	.682
7500	403.1	82.5	1.155	.573	.662
7500	403.6	82.7	1.157	.570	.659
7500	403.6	82.9	1.156	.570	.658
7500	404.7	83.0	1.157	.568	.657
7500	407.5	83.8	1.164	.559	.650
7500	417.5	86.8	1.176	.531	.624
7500	418.6	86.6	1.184	.528	.625
7500	418.6	87.8	1.176	.528	.621
7500	419.2	87.8	1.172	.528	.619
7500	419.2	87.1	1.177	.528	.621
7500	439.7	101.5	1.153	.463	.534
7500	439.7	100.4	1.166	.463	.539

Table 1 (Continued). Viscosity of Steam - Experimental Data

P (psia)	T (Deg. Cent)	Reynolds No.	ν /cm^2/sec) x 1000	Density (gm/cc)	μ (gm/cm sec) x 1000
7500	440.3	105.6	1.129	.454	.512
7500	440.8	102.0	1.167	.454	.530
7500	441.4	108.1	1.101	.454	.500
7500	454.7	113.2	1.191	.405	.482
7500	456.9	111.5	1.233	.394	.485
7500	458.6	115.1	1.212	.390	.472
7500	460.2	115.5	1.230	.383	.471
7500	461.4	116.7	1.229	.379	.466
7500	466.9	120.4	1.275	.358	.456
7500	467.5	119.3	1.284	.358	.459
7500	468.0	123.1	1.250	.355	.444
7500	468.6	119.6	1.285	.355	.456
7500	469.1	120.0	1.294	.352	.455
7500	493.5	128.3	1.497	.284	.425
7500	494.1	133.3	1.442	.284	.409
7500	494.7	130.5	1.477	.284	.419
7500	494.7	129.4	1.490	.284	.423
7500	496.3	130.4	1.495	.280	.418
7500	547.9	97.2	1.881	.209	.393
7500	550.2	109.5	1.867	.207	.386
10,000	403.6	62.9	1.117	.627	.700
10,000	404.2	63.3	1.113	.624	.695
10,000	404.2	63.4	1.116	.624	.696
10,000	445.8	70.1	1.176	.533	.627
10,000	447.5	73.9	1.117	.531	.593
10,000	447.5	74.2	1.115	.531	.592
10,000	474.7	81.2	1.164	.464	.540
10,000	474.1	82.6	1.151	.464	.534
10,000	474.7	82.5	1.153	.464	.535
10,000	488.6	86.0	1.198	.428	.513
10,000	489.7	86.0	1.205	.424	.511
10,000	516.9	94.2	1.291	.362	.467
10,000	518.5	94.8	1.289	.360	.464
10,000	518.0	94.7	1.290	.360	.464
10,000	519.1	95.1	1.291	.358	.462

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